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Update of the like-sign dimuon charge asymmetry measurement from the D0 experiment

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The D0 Collaboration has published three measurements of the CP-violating like-sign dimuon charge asymmetry in $p\bar{p}$ collisions at the Fermilab Tevatron collider. These measurements are significantly different from the standard model predictions. In this presentation, we discuss the status of the final measurement of this asymmetry and the expected improved sensitivities, using the full 10.4 fb^{-1} data sample collected during Run II, and discuss its possible interpretations.

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1 Introduction: the Mystery and the Motivation

The single inclusive muon and like-sign dimuon charge asymmetries are defined as the ratios of the difference and sum of the rates $a_{CP} = \{\Gamma(\mu^+) - \Gamma(\mu^-)\} / \{\Gamma(\mu^+) + \Gamma(\mu^-)\}$ and $A_{CP} = \{\Gamma(\mu^+\mu^+) - \Gamma(\mu^-\mu^-)\} / \{\Gamma(\mu^+\mu^+) + \Gamma(\mu^-\mu^-)\}$. The standard model (SM) predictions of the charge asymmetry induced by CP-violation are small in magnitude compared to the current experimental precision, so non-zero measurements would indicate new sources of CP-violation. D0 has previously published three measurements of the CP-violating like-sign dimuon charge asymmetry in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermi lab Tevatron collider. These measurements were at integrated luminosities of 1 fb^{-1} [1], 6.1 fb^{-1} [2], and 9 fb^{-1} [3], each observing A_{CP} with differences from the standard model predictions of 1.7 to 3.9σ significance. This is one of only a few apparent inconsistencies with the standard model.

The major questions to be answered are whether these observations of deviation from the standard model are real, is our understanding of the SM complete, and is there something else going on beyond the SM?

A new analysis of the full Run II data set of 10.4 fb^{-1} with improved background subtraction and upgraded analysis methodology is currently under collaboration review. It is not yet ready for public release, so I can only give a status report, show the checks performed using single inclusive muons, and give an indication of the expected sensitivities. The slides presented at DPF2013, with additional figures, are available at Reference [4].

2 Theoretical Framework

In the standard model, one manifestation of CP-violation is in the mixing of the neutral B mesons $B^0 \leftrightarrow \bar{B}^0$ and $B_S^0 \leftrightarrow \bar{B}_S^0$. This asymmetry can be observed in the decays of pairs of particles containing b and \bar{b} quarks. Pairs of b and \bar{b} quarks are produced symmetrically in the $p\bar{p}$ collisions. These quarks hadronize into pairs of B and \bar{B} particles, including baryons. For example, particles containing b quarks can have the decay chain $b \rightarrow \mu^- + X$, while particles containing \bar{b} quarks can have the decay chain $\bar{b} \rightarrow \mu^+ + X$. For these direct decays, the negative charge of this “right-sign” muon will tag the b flavor of the parent quark. The other \bar{b} quark can decay $\bar{b} \rightarrow \mu^+ + X$, producing an opposite-sign dimuon $\mu^+\mu^-$ pair. However, for example, the parent b quark could hadronize into a \bar{B}^0 which could then oscillate into a B^0 which then can decay into a “wrong-sign” $\mu^+ + X$, schematically $b \rightarrow \bar{b} \rightarrow \mu^+$. So the oscillation of either $B^0 \leftrightarrow \bar{B}^0$ or $B_S^0 \leftrightarrow \bar{B}_S^0$ can produce same sign dimuons. CP-violation occurs if the rate $\Gamma(B^0 \rightarrow \bar{B}^0)$ does not equal the rate $\Gamma(\bar{B}^0 \rightarrow B^0)$, or $\Gamma(B_S^0 \rightarrow \bar{B}_S^0) \neq \Gamma(\bar{B}_S^0 \rightarrow B_S^0)$, which can produce an observable charge asymmetry for the like-sign dimuons for $\Gamma(\mu^+\mu^+) \neq \Gamma(\mu^-\mu^-)$. The sequential decays $b \rightarrow c \rightarrow \mu^+$

are background sources of wrong-sign muons. Using the Pythia [5] simulation for the total number of muons from b -particles, D0 observes approximately 73% $b \rightarrow \mu^-$; 11% $b \rightarrow \bar{b} \rightarrow \mu^+$; and 16% $b \rightarrow c \rightarrow \mu^+$.

Previously, the only source of charge asymmetry for these like-sign dimuons in the standard model was considered to be via CP-violation in mixing. The predicted magnitude of this effect in D0 is $A_{CP}^{\text{mixing}}(\text{SM}) = (-0.008 \pm 0.001)\%$. Recently, however, G. Borissov and B. Hoeneisen [6] have calculated an additional CP-violating contribution due to the interference between processes involving identical CP-definite states that can be reached both via mixing and non-mixing paths. For example, a B^0 can produce a wrong sign μ^+ via the CP-even final state $D^- D^+$ where the $D^+ \rightarrow \mu^+ X$ decay. The B^0 can produce $D^- D^+$ either directly or by first oscillating into \bar{B}^0 which can also decay into $D^- D^+$. There is interference and CP-violation between the two paths. This interference does not contribute to a_{CP} for single muons since the rates for $D^+ \rightarrow \mu^+$ and $D^- \rightarrow \mu^-$ balance.

To set the scale, for the D0 like-sign dimuon charge asymmetry, this interference term is calculated to be $A_{CP}^{\text{int}}(\text{SM}) = (-0.035 \pm 0.008)\%$, or about 4 times $A_{CP}^{\text{mixing}}(\text{SM})$. So $A_{CP}(\text{SM}) = A_{CP}^{\text{mixing}}(\text{SM}) + A_{CP}^{\text{int}}(\text{SM}) = -0.043 \pm 0.010\%$ which can be compared with the previously measured $A_{CP}(\text{D0}, 9 \text{ fb}^{-1}) = (-0.276 \pm 0.092)\%$ [3].

A_{CP}^{int} is linearly dependent on $\Delta\Gamma_d/\Gamma_d$, the ratio of the difference of the widths of the light and heavy members of the mass eigenstates, $\Gamma(B_d^{\text{light}}) - \Gamma(B_d^{\text{heavy}})$, to their average. This, then, gives the possibility of measuring $\Delta\Gamma_d/\Gamma_d$ in this analysis. The current World Average [7] for $\Delta\Gamma_d/\Gamma_d$ is $(1.5 \pm 1.8)\%$, while the SM prediction [8] is $(0.42 \pm 0.08)\%$. It is anticipated that in this analysis, D0 will be able to measure $\Delta\Gamma_d/\Gamma_d$ to $\approx 1\%$ (absolute) precision. Interference between such mixed and non-mixed paths for B_s^0 is too small to be observable in the D0 data set. The analogous $\Delta\Gamma_s/\Gamma_s$ for B_s^0 is much smaller than for B_d^0 and is already well determined [7, 8].

3 Experimental Situation

The three prior D0 analyses [1, 2, 3] of the CP-violating like-sign dimuon asymmetry consistently measured A_{CP} in the range -0.25 % to -0.28 % which differed from the predictions of the standard model (assuming mixing only, without the interference between the mixed and non-mixed paths) by significances of 1.7 to 3.9 σ . Table 1 shows the evolution of the D0 measurement of A_{CP} with increasing integrated Luminosity and sophistication of the analysis. The A_{CP} results from this analysis of the full 10.4 fb^{-1} data set, with reduced systematic uncertainties will be compared with the sum of $A_{CP}^{\text{mixing}} + A_{CP}^{\text{int}}$.

$\int \mathcal{L} dt$	Asymmetry A_{CP}	deviation from SM	Reference
1.0 fb ⁻¹	$(-0.28 \pm 0.13 \pm 0.09)\%$	1.7 σ	[1] (2006)
6.1 fb ⁻¹	$(-0.252 \pm 0.088 \pm 0.092)\%$	3.2 σ	[2] (2010)
9.0 fb ⁻¹	$(-0.276 \pm 0.067 \pm 0.063)\%$	3.9 σ	[3] (2011)
10.4 fb ⁻¹	$(???? \pm 0.064 \pm 0.055)\%$? σ	in preparation (2013)

Table 1: Evolution of the D0 measurement of A_{CP} for the like-sign dimuon charge asymmetry.

4 Experimental Methodology

Why is D0 [9] a good place to measure the like-sign dimuon charge asymmetry? The CP-symmetric initial $p\bar{p}$ state does not have a charge asymmetry in the central region, or when integrated over a symmetric range of $\pm \eta$. Due to the large amount of hadronic absorption in the U-LAr Calorimeter and the tracking through the muon toroids [10], D0 has excellent muon identification [11]. The magnetic field directions in the central tracking solenoid magnet [9] and in the muon toroids [10] are cycled through all combinations on a regular basis which allows for cancellation of first-order effects due to instrumental asymmetries.

We observe a sample of 2.2×10^9 single μ^\pm , 2.2×10^7 opposite sign $\mu^+\mu^-$, and 6.2×10^6 $\mu^\pm\mu^\pm$ like-sign dimuons.

For analysis, the data are primarily divided into three muon (transverse) Impact Parameter (IP) bins (IP=1, 2, 3) corresponding to (0-50 μm), (50-120 μm), and (120-3000 μm), and a sum integrating over ALL IP. The muons of interest from b decays are predominantly at large IP, while the muons from the decays of kaons and pions are predominantly at small IP, since the parent kaons and pions have already been tracked from the primary vertex before decaying. Each of these four IP sets are also sub-divided into a combination of nine ($p_T, |\eta|$) bins:

Bins # 1-3: $0 \leq |\eta| \leq 0.7$, $p_T = 4.2$ -5.6, 5.6-7, 7-25 GeV;

Bins # 4-5: $0.7 \leq |\eta| \leq 1.2$, $p_T = 3.5$ -5.6, 5.6-25 GeV;

Bins # 6-9: $1.2 \leq |\eta| \leq 2.2$, $p_T = 1.5$ -3.5, 3.5-4.2, 4.2-5.6, 5.6-25 GeV.

Standard D0 single- and multi-muon triggers and analyses [1, 2, 3] are used, along with slightly tighter requirements on tracking quality. To ensure that the muon candidates penetrate through the muon toroids, we require either $p_T > 4.2$ GeV or $|p_z| > 5.2$ GeV. We also require $p_T < 25$ GeV to avoid muons from W^\pm and Z^0 decays. The dimuon invariant mass $M_{\mu\mu}$ is required to be greater than 2.8 GeV to avoid both muons from the decay chain of the same b quark $b \rightarrow \mu^- \nu c$ ($\rightarrow \mu^+$).

Based on the muon charge configuration of number of events observed n^\pm , N^{++} , and N^{--} , the raw (observed) asymmetries (in each IP, $p_T, |\eta|$) bin are defined as: $A = (N^{++} - N^{--})/(N^{++} + N^{--})$ and $a = (n^+ - n^-)/(n^+ + n^-)$ for like-sign dimuons

and for single inclusive muons, respectively. The background subtracted residual CP asymmetries are $a_{CP} = a - a_{bkg}$ and $A_{CP} = A - A_{bkg}$, where $a_{bkg} = a_\mu + f_K a_K + f_\pi a_\pi + a_p$. f_K is the fraction of charged kaons in the μ sample, measured using dedicated channels with final-state kaons reconstructed as muons. a_K is the asymmetry is due to the difference in the inelastic cross sections between K^+ and K^- . $f_K a_K$ is typically +0.62% and is the dominant background term at low IP. a_μ is the muon detector charge asymmetry measured with $J/\psi \rightarrow \mu^+ \mu^-$. a_μ is typically -0.29% and is the next dominant background term. $f_\pi a_\pi$ and a_p are considerably smaller. In the current analysis, f_K and f_π are cross-checked using tracks measured in both the central tracker and in the local muon detector trackers. The differences in the two measurements of the muon fractions are included in the systematic uncertainties.

5 Checks and Projections of Sensitivities

The standard model predicts the magnitudes of the CP asymmetries a_{CP} for single inclusive muons for all of the (IP, p_\perp , $|\eta|$) bins which are well below the sensitivity limits of the D0 10.4 fb⁻¹ data. Therefore, D0 expects the measurements of these CP asymmetries for single inclusive muons to be consistent with zero. The single muon data serves as a closure test or consistency check that we are not generating false asymmetries through the apparatus, the acceptances, the analysis, or the background subtractions. To illustrate the preliminary resolutions and data scatter for the 10.4 fb⁻¹ data, Figure 1 shows the raw, observed asymmetries a (upper histogram), measured background asymmetries a_{bkg} (upper data points), and the background subtracted CP violating asymmetries $a_{CP} = a - a_{bkg}$ (lower data points) for each of the 9 (p_\perp , $|\eta|$) bins, for ALL IP and for the three IP bins. The $a_{CP} = a - a_{bkg}$ plot for ALL IP demonstrates consistency with the expected zero asymmetry, along with the uncertainty spread for the average over the nine (p_\perp , $|\eta|$) bins.

Before the interference term was included in the like-sign dimuon phenomenology, the 9 fb⁻¹ analysis [3] used only two IP bins of IP < 120 μm and IP > 120 μm and the sum over all IP. This produced the three linear correlation bands between a_{sl}^d and a_{sl}^s along with their correlated 68% and 95% CL uncertainty ellipses in Figure 2. Given the fitting over three independent IP bins and the 9 (p_\perp , $|\eta|$) bins, and the upgraded background subtraction and analysis, D0 anticipates that the *areas* of these uncertainty ellipses will decrease by $\approx 44\%$. The D0 direct measurements of $a_{sl}^d = (0.68 \pm 0.47)\%$ from $B^0 \rightarrow D^{(*)-} \mu^+ X$ [14] and $a_{sl}^s = (-1.12 \pm 0.76)\%$ from $B_s^0 \rightarrow D_s^- \mu^+ X$ [15] are overlayed for comparison.

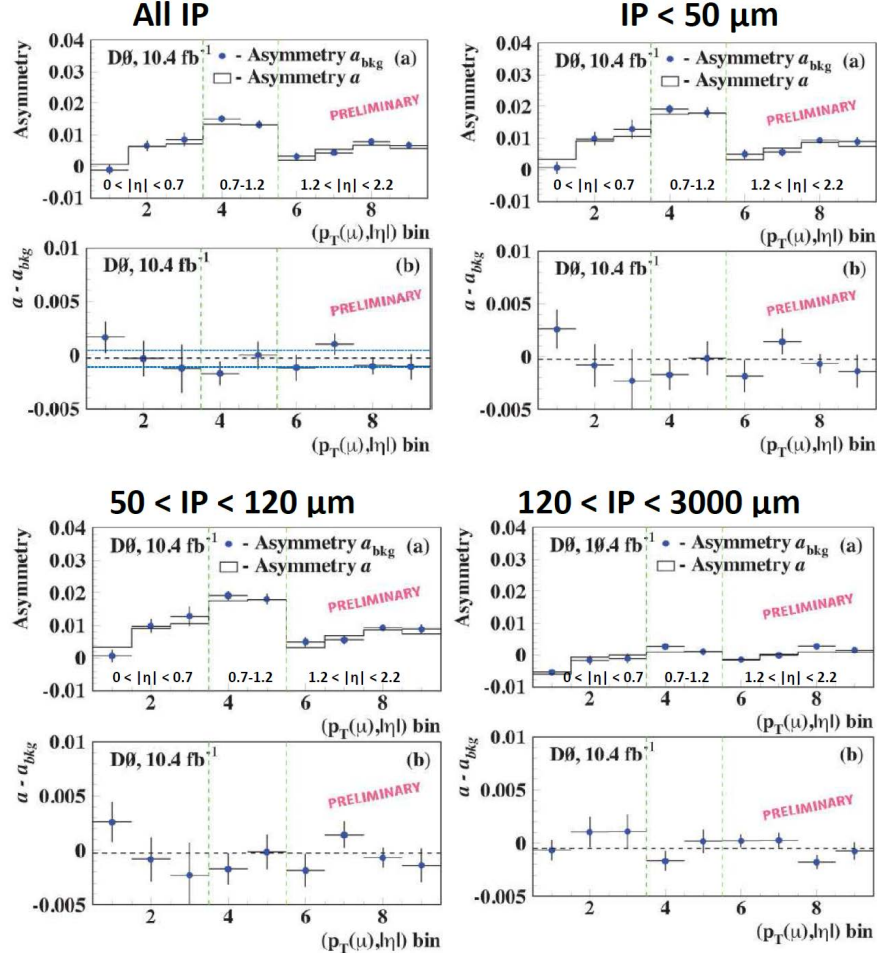


Figure 1: The raw, background, and CP violating asymmetries for single inclusive muons for ALL IP and the three IP ranges and the 9 bins in $(p_T, |\eta|)$.

6 Summary

D0 is preparing the final release of the analysis of the CP violating like-sign dimuon analysis based on the full 10.4 fb^{-1} Run II data set. This result is anticipated to have an uncertainty on the asymmetry A_{CP} of $\pm 0.084 \%$ (stat. + syst.), allowing more stringent comparison with the predictions of the standard model. This analysis will also decrease the area of the uncertainty ellipse for the semi-leptonic decay asymmetries a_{sl}^d and a_{sl}^s by a factor of $\approx 44 \%$.

Remaining questions to be addressed are whether the entire like-sign dimuon charge asymmetry could be due to a large value of $\Delta\Gamma_d/\Gamma_d$; whether there are still missing SM contributions not included in the calculation of A_{CP} ; and whether the D0 observation of significant deviations from the SM predictions is real. Addressing

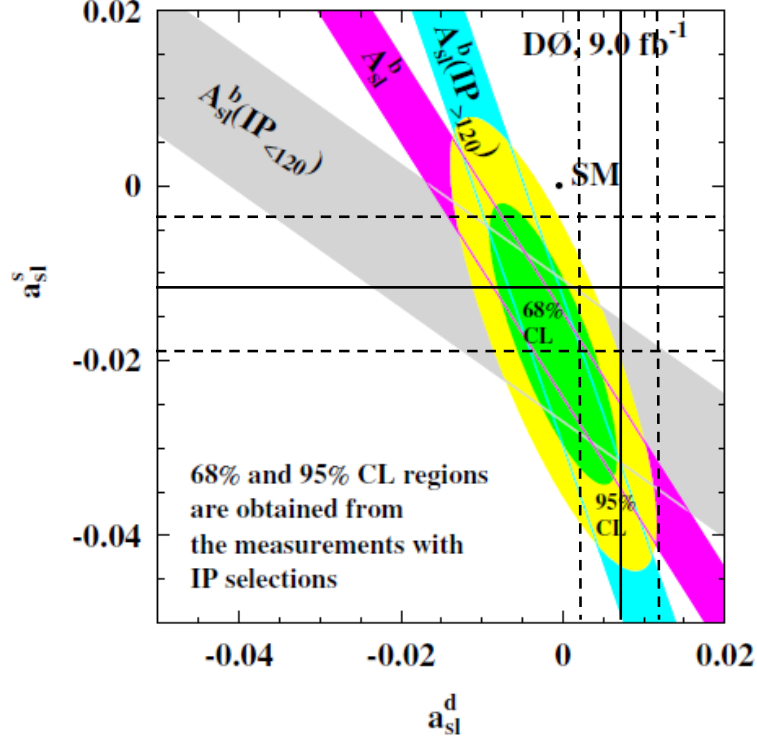


Figure 2: The a_{sl}^d vs. a_{sl}^s measurement and uncertainty ellipse contours for the prior 9 fb^{-1} D0 same sign dimuon charge asymmetry analysis [3] compared to the SM predictions. The horizontal and vertical solid and dashed lines represent the measurements $\pm 1 \sigma$ bands from recent D0 inclusive semi-leptonic decay measurements of a_{sl}^d and a_{sl}^s [14, 15].

the latter will require verification by other experiments.

The final D0 paper on CP-violation for like-sign dimuons based on this analysis has been submitted for publication in early October, 2013 [16].

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